RECENT WORK IN MAGNETOTELLURIC SOUNDINGS OF THE LOWER CRUST AND UPPERMOST MANTLE

H. FOURNIER

Laboratoire de Geomagnetisme du Centre de Recherches Geophysiques du C.N.R.S.
24 rue Lhomond, Paris (5e), France

Abstract. The technique of magnetotelluric sounding has been used for 25 years and a wealth of information has been obtained from regional studies. A table of results and an accompanying extensive bibliography was presented to the Murnau Workshop and this review discusses some aspects derived from the accumulated literature. In particular, the deep conducting layer (CCU) is considered.

1. Introduction

In 1978, we celebrated the twenty-fifth anniversary of the method of magnetotelluric sounding proposed by Cagniard (1953a, b). Since then the method has been developed in a satisfactory way both in the domain of oil prospection – but we shall not be concerned here about that, as it does not play a part in this review – and in the domain of the physics of the solid earth – a subject which we are attempting to present with emphasis on relatively new work (of the last ten years, approximately).

However, I encounter several difficulties in writing this review. In fact, the essential results of magnetotelluric soundings concerning the lower crust and the uppermost mantle are presented in two parallel reviews, Kovtun (1976) and Hutton (1976a). These studies resulted from the 'Third Workshop on Electromagnetic Induction in the Earth', held in this same year of 1976 at Sopron (Hungary). The review of Kovtun treats 'Induction studies in stable shield and platform areas'. Hutton presents the results of the same methods in 'Induction studies in rifts and other active regions'. Results both from magnetotelluric sounding and from geomagnetic depth sounding are given there. These two studies are well presented and remarkably complete. Moreover, in the 1976 Workshop the use of magnetotelluric soundings for geothermal investigations was considered by Stegena (1976) and Ádám (1976). We have to add that Hutton (1976b) has written a monograph which encompasses the subject to be treated here. And last, but not least, we have to mention the monograph published in 1976 by the Hungarian Academy of Sciences (1976). This is a monumental ensemble of 750 pages on geo-electricity and geothermics given by about one hundred authors.

Taking into account that a bibliographic search has revealed only a few titles after 1976, there is little new to report on the proposed subject. Consequently, I presented a general table at the Murnau Workshop and shall here attempt to treat some particular aspects of the subject. It must be admitted that some of the conclusions I shall discuss are rather debatable.

Geophysical Surveys 4 (1980) 89-96. 0046-5763/80/0041 – 0089$01.20.

2. The Table

The production of the general table was inspired by reviews, which I presented in Mons (Fournier, 1962), in Budapest (Fournier, 1963), and in 1971 also in Budapest (Fournier *et al.*, 1971). Copies of the general table and associated bibliography were distributed in Murnau and further copies are available on request.

3. Remarks

(a) *Conductive Channelling*

A subject of great importance is to draw attention to the conduction phenomenon, which is superposed on that of local induction. Compared with local induction this conduction effect is important in cylindrical conductive structures, which are open at both ends to the sea, the ocean, or an equivalent conductor.

The studies, over several years, of differential geomagnetic soundings in real time by the school of Mosnier, have shown the importance of this phenomenon, in particular in the case of the so-called 'Pyrenean anomaly' and more recently in the case of the Rhine-graben (Babour *et al.*, 1976; Babour and Mosnier, 1977; Mosnier and Babour, 1978; Albouy *et al.*, 1978). Weidelt (1977) treated the theoretical aspect of this question at Sopron.

Let us look at the possible consequence of this phenomenon for magnetotelluric soundings. Admitting that in the case of the M-T soundings of Haak and Reitmayr (1974) and Reitmayr (1975) in the Rhine Valley the telluric NS-component is enhanced to twice the normal value to be expected from local induction – this is a working hypothesis only – the upper boundary of the intermediate conductive layer, placed by the authors at a depth of 25 km, would in reality be situated at a depth of 12 km.

This might apply also to numerous M-T soundings on the large channelling systems, on grabens, and possibly also to the magnetic anomaly of the Basin of Paris. Hence, the interpretations of M-T soundings on these kinds of structures have to be considered with reservations.

On the other hand, it would be interesting to study a conducting cylindrical structure, which is closed at its ends, both by the methods of M-T sounding and by differential geomagnetic sounding (in real time – or otherwise).

(b) *Isolated Deep M-T Soundings*

There are inherent risks in the interpretation of the curves of an isolated deep M-T sounding. This is generally so when the M-T data published by the geomagnetic observatories are exploited. In fact, the study of the site of the observatory which has furnished the data of the magnetic and telluric variations, is generally not connected with a regional survey of supplementary M-T soundings for medium depths. In this case it is not possible to apply the statistical mean averaging methods of interpretation proposed by Porokhova, (1975), by Fournier *et al.*, (1974), and by Berdichevski *et al.*, (1978).

The list of geomagnetic observatories which have been the object of an isolated deep M-T sounding comprises Tortosa and Toledo in Spain, Pilar in Argentina, M-Bour in Senegal, Zaria and Ibadan in Nigeria, and perhaps Odessa in the Ukraine. On the other hand, Borok and its surroundings (NE of Moscow) have been well studied; the same applies also to Central Europe observatories.

I would like to say that an isolated deep M-T sounding is in any case better than nothing.

(c) *The Deep Conducting Layer (Couche Conductrice Ultime CCU)*

In 1962, I proposed to map the upper boundary of the deep conductive layer by means of M-T soundings (Fournier, 1962). In fact, it was the results of Weise (1962) combined with my results, which were decisive for this proposal. What credibility can be ascribed to such a map? It should correspond in its main features to the map determined by Berdichevsky *et al.* (1973) using multifrequency geomagnetic profiling, which is less affected by local geological pertubation. In a certain way, this would provide mutual assitance to both methods, if they yield the same results, of course, for the main features. For instance, the slope of 10% towards the west in western France, which is proposed by this map (Berdichevsky *et al.*, 1973), can provoke some doubt. Does the study of Aubert (1974) express in a certain way this regional variation? If the broad features of the deep M-T interpretation confirm the phenomenon, this would be encouraging confirmation of the reliability of the two methods for the west of France.

It is necessary to state that the existence and average depth of the deep conductive layer was proposed as long ago as the nineteenth century (and at the beginning of the twentieth century) by the great classics: we do not pretend to invent it; perhaps the M-T method can resolve regional or local details, although there may be some risks in the interpretation.

If a satisfactory agreement between M-T results and the contours of the depth of the CCU (Berdichevsky *et al.*, 1973) could be achieved, it would provide encouragement for the magnetotelluric method and consequently we could also have confidence in results obtained at medium depth – intermediate conducting layers which may relate to low velocity layers, to the asthenosphere and project ELAS, etc. – taking into account the precautionary measures as proposed by Berdichevsky *et al.*, (1976).

This map is not made in the regions of the oceans and the equatorial electrojet. Are there important differences in the oceanic and continental regions? Clearly magnetotelluric studies are of interest both at the bottom of the oceans and on the ice-pack of the Arctic. It appears that the zone of the equatorial electrojet is more difficult with respect to interpretation than the oceanic zones, whereas the latter pose more technological difficulties.

On the other hand, one may ask whether it is the same deep conductive layer which has been discovered at very different depths by M-T soundings using periods up to the diurnal variation: the depth at Borok and its surroundings (NE of Moscow) is 200–230 km approximately; 600–700 km in France and Spain; 200 km (or less) in the region of Irkutski; 1000 km at Tucson (Tichonov, 1950); 600–650 km in Central Russia–Ukraine; 570 km in the south of the Ural; 380 km for the region of Gottingen (Hempfling, 1977) and after Haak 300 km in the Afar-depression. We add the figure 380 km for Idaho, a result obtained by Camfield and Gough (1975) using geomagnetic soundings.

In 1964 at Leipzig (Fournier, 1964) I drew attention to the point that in establishing a map of the upper boundary of the deep conductive layer, the exploitation of M-T data at periods as short as 2–3 hours enables isolines of changing resistivity at great depth to be determined. Hence it is not necessary to determine at every site the depth corresponding to the diurnal variations. It is sufficient to operate only one central station, which exploits the sounding up to the diurnal period.

I add here that for Western Europe Pecova *et al.* (1977) appear to be in agreement with Mechler *et al.* (1971): strong conduction at a depth lower or equal to 700–800 km on the one hand and a change of seismic velocity at depth of about 650 km on the other hand (9.3 to 10.2 km/sec).

(d) *Some Suggestions for Research*

It will be interesting to make more parallel studies between deep magnetotelluric and seismic soundings. In particular, investigations should be made into the possibility of a striking correspondence between the intermediate conductive layers and the low velocity layers. In cooperation with Ward and Morrison, I proposed this idea in 1963 at the University of Berkeley (Fournier *et al.*, 1963). The project ELAS, accepted in 1977 in Seattle by IAGA, is based on the same ground: the study of the asthenosphere by magnetotelluric and magnetovariational soundings.

Another field of application of the magnetotelluric sounding is the study of plate contacts: The Red Sea is an ideal case for an opening ocean. The profile should be extended rather far into Egypt or Soudan to the west and Arabia to the east. It would require some recordings at the bottom of the Red Sea. In my opinion, the Afra-depression and the African grabens which are easier regions to study have not opened enough. In other words, they are regions without a long enough evolution in time and in space. With my colleagues from South America – actually the Argentines only – (the Brazilian group (Sao Jose dos Campos) is yet to be organized and equipped) – we have started to study the destructive contact of the Nazca plate in the region of the 32nd southern parallel (Febrer *et al.*, 1977; Febrer *et al.*, 1979). The case of the gliding contact could certainly be found and studied.

I think that the magnetotelluric study of paleozoic crystalline massifs could reveal information about the sense of the compression. A map with the directions corresponding to Rho_{max} and Rho_{min} would yield this information for periods appropriate to the thicknesses considered in the crystalline basement. This might be applicable to the study of Planchez-du-Morvan (Fournier *et al.*, 1973).

I recommend, as long as it is still possible, conducting complete M-T studies at actual geomagnetic observatories. It will be necessary to install telluric lines either near the geomagnetic station or some kilometers away, if the local electric noise is too dominant near the observatory. It would be necessary to record for about one year to see if there is a seasonal variation of the average Rho for the diurnal period and its harmonics, as in the remarkable case at the geomagnetic observatory of M-Bour (Senegal) (Fournier and Metzger, 1977). This could be a project to be submitted to the next General Assembly of IAGA at Canberra in 1979.

Together with my colleagues Metzger and Febrer I have studied the scattering of M-T sounding curves, when the same kind of data, coming from different sites with different structural settings are analysed using a certain number of different programs for tensorial M-T analysis. In the present state of our study there does appear to be scatter. It is too early to decide whether this scattering is acceptable or not – and what could possibly be the reason (or explanation) and what could be the absolute criterion for the best processing program. This preliminary result suggests one should be careful when using the method of magnetotelluric sounding. It has its advantages and its limitations as do all methods.

Concerning magnetotelluric soundings to be made in the electrojet zone, approximately 600 km on each side of the magnetic equator, one must remember the difference in the magnetic activity between day and night – studies up to a period of two hours are primarily interesting at night, when they are mostly not pertubed by the electrojet effect – this period is in general long enough to reach the deepest conducting layer. On the other hand, long analyses for many days in the electrojet zone are interesting but the results are completely unpredictable. Some M-T long period analyses were made in Nigeria for Zaria magnetic observatory, below the magnetic equator (Mbipom, 1977) and for Ibadan magnetic observatory below the southern limit of the electrojet zone (Akintobi, 1970; Fournier *et al.*, 1971; Fournier *et al.*, 1972) they remain uncertain and are as yet unconfirmed. This kind of long analysis may provide data for the discussion about the existence of induction effects associated with the electrojet field – if there is no true induction effect, the M-T curve should be infra-asymptotic in the diurnal decade of log T. (The amplitude of the E field at the diurnal period and its harmonics doesn't change, even though the amplitude of 'H' is much greater.)

Geothermal M-T studies show in general, good agreement among lower resistivities measured over a regional area, but a very variable effect on the Rho values for local studies, because the tectonics associated with the hot spot of the crust perturbs the results of the analysis. This kind of M-T study is sometimes locally discouraging.

The M-T method will be useful in studying the characteristics of the layers immediately below the ice of Greenland and Antarctica; see Lefevre *et al.* (1957) and Fig. 65, p. 123, of the Tomus II from Fournier (1970).

(e) *Some Final Reflections*

As we remark, in the early days of the M-T method in the sixties, the Eastern countries were busy mostly with M-T basement determinations in the great plains of U.S.S.R.

(Europe and Asia), about 110 field teams were operating in the peak epoch (Kunetz, 1965) – meanwhile western countries were most interested in deep M-T soundings (see the first M.S. Thesis in M-T Research: Webster (1957), the first Ph.D. Thesis: Cantwell (1960)). In the seventies the contrary appears: there is interest in deep M-T sounding in the U.S.S.R., mostly after the decision of 1972, and there is more interest in oil research with the M-T method in North American regions. During these two decades 1960 to 1978 Western Europe remains in a mean evolving position between the two extremes. Consequently, we are beginning now to obtain initial interpretation for some great sedimentary basin comprising nearly the first hundred kilometers depth.

Another kind of interesting average is the mean aspect of the participation in the two Earth Electromagnetic Workshops at Sopron (1976) and Murnau (1978): the exchange and contacts between scientists of Western and Eastern countries is perfectly normal – although at the first Workshop in Edinburgh, the Eastern participation was limited. We could hope for Chinese participation in the future. I think that the Chinese scientists are working in M-T soundings – unfortunately, the *Acta Geophysica Sinica* are as yet mostly in the Chinese language and consequently it is not simple (for me) to present and use their results.

The aim of this review is modest: to introduce the principal field studies in magnetotelluric soundings concerning the lower crust and upper mantle. I asked my colleagues to complete this review by letting me know the references of the papers, which I did not find, and by giving their advice for improvements. I thank them, I thank especially B.A. Hobbs from the Department of Geophysics of the University of Edinburgh.

I attribute at least the same theoretical importance and at least the same practical interest to the method of *geomagnetic depth sounding* (largo sensu) – compared with the method of *magnetotelluric sounding*. These two great methods started simultaneously in 1950 in Gottingen, Moscow, Paris and Tokyo (listed in alphabetic order) (Fournier, 1965, 1966, 1969). These two families of geoelectromagnetic methods are inseparable. As proof, the possibility of obtaining M-T maps for the deep layers is to be expected with the transposition method proposed by Osipova *et al.* (1978) applied in North America using a geomagnetic deep sounding array plus one M-T deep sounding as an absolute reference.

References

Ádám, A.: 1976, *Acta. Geodaet., Geophys. et Montanist. Acad. Sci. Hung.* **11**(3-4), 503-509.

Akintobi, J.A.: 1970, 'Earth current and geomagnetic variations in Nigeria', Ph.D. Thesis, Univ. of Ibadan, Nigeria.

Albouy, Y., Babour, K., and Boitier, F.: 1978, 'Some properties of the geomagnetic anomaly of the Rhinegraben', Abstract, Fourth Workshop on Electromagnetic Induction in the Earth and Moon, Murnau, Germany.

Aubert, M.: 1974, *Phys. Earth Planet. Int.* **9**, 364-366.

Babour, K., Mosnier, J., Daignieres, M., Vasseur, G., Le Mouel, J.L., and Rossignol, J.C.: 1976, *Geophys. J.R. Astr. Soc.* **45**, 583-600.

Babour, K., and Mosnier, J.: 1977, *Geophysics* **42**, 66-76.

Berdichevsky, M.N., Borisova, V.P., Kolomijtseva, G.I., Rotanova, N.M., and Feinberg, E.B.: 1973, *Inst. Terr. Magn. Ion. and Radiowave propag. (IZMIRAN)*, preprint No. 10.

Berdichevsky, M.N., and Dmitriev, V.I.: 1976, *Acta. Geodaet., Geophys. et Montanist. Acad. Sci. Hung.* 11(3-4), 447-483.

Berdichevsky, M.N., Vanyan, L.L., Kuznetsov, V.A., Nechaeva, G.P., Okulusski, B.A. and Shilovski, P.P.: 1978, 'The geoelectric model of the Baikal region and the USSR asthenospheric zones', Abstract, Fourth Workshop on Electromagnetic Induction in the Earth and Moon, Murnau, Germany.

Cagniard, L.: 1953a, *Ann. Geophys.* 9(2), 95-125.

Cagniard, L.: 1953b, *Geophysics* 18(3), 605-635.

Camfield, P.A., and Gough, D.L.: 1975, *Geophys. J.R. Astr. Soc.* 41, 193-218.

Cantwell, T.: 1960, 'Detection and analysis of low frequency electromagnetic signals', Ph.D. Thesis, M.I.T.

Febrer, J., Demichelli, J., Garcia, E., and Fournier, H.G.: 1977, *Acta Geodaet., Geophys. et Montanist. Acad. Sci. Hung.* 12(1-3), 29-31.

Febrer, J., Baldis, B., and Fournier, H.G.: 1979, 'The deep magnetotelluric sounding at Chamical, Proia de La Rioja, Argentine', Abstract Xa Reunion Cientifica Ass. Argentina de Geofis. y Geodes. San Juan, Argentina.

Fournier, H.G.: 1962, *Bull. Inf. Ass. Ing. Fac. Polyt. de Mons*, 10, 4-10.

Fournier, H.G.: 1963, *Acta. Techn. Hung.* 43(3-4), 453-466.

Fournier, H.G.: 1964, *Geophysik und Geologie*, Folge 6, Leipzig, 34-50.

Fournier, H.G.: 1965, 'Place historique de la méthode magnétotellurique dans l'ensemble des méthodes electromagnétiques d'investigation de la Croûte et du Manteau, (Terre-Induction)', Edition du Bicentenaire de l'Acad. Min. de Freiberg.; *Inst. Phys. Globe, Paris*, 260 pp. Dépôt Légal Centre National Recherche Scientifique, Paris.

Fournier, H.G.: 1966, *Inst. Phys. Globe, Paris*, Note 17, Bibliothèque Nationale. D.L. 17199-66 et Bibliothèque du Congres A-B/Afo 50110.

Fournier, H.G.: 1969, *Ensayo Historico de los Conocimientos Magnetoteluricos*, Traducido por Mercedes B. de O'Neill. Observatorio Magnetico del Ebro, Tortosa, Espana, 320 pp.

Fournier, H.G.: 1970, 'Contribution au développement de la méthode magnétotellurique, notamment en vue de la determination des structures profondes', Th. Doct. Fac. Sci. Paris.

Fournier, H.G., Ádám, A., Akintobi, J., de Miguel, L.G.M., Metzger, J. and Sanclement, E.: 1971a, Abstract, XV General Assembly of Int. Ass. Geomag. Aeron., Moscow.

Fournier, H.G., Ádám, A., de Miguel, L., and Sanclement, E.: 1971b, *Acta. Geodaet., Geophys. et Montanist. Acad. Sci. Hung.* 6(3-4), 459-477.

Fournier, H.G., Babour, K., Dupis, A. and Clerc, G.: 1974, Abstract, 2nd Workshop on Electromagnetic Induction in the Earth, Ottawa.

Fournier, H.G., Benderitter, Y., and Febrer, J.: 1973, Abstract, Sec. Gen. Ass. IAGA, Kyoto.

Fournier, H.G., and Metzger, J.: 1977, Abstract, Vè Réun. Ann. Sc. de la Terre, Rennes.

Fournier, H.G., Oni, C.E.S., and Akintobi, J.A.: 1972, Abstract, 1st Workshop on Electromagnetic Induction, Edinburgh.

Fournier, H.G., Ward, S.H., and Morrison, H.F.: 1963, Tech. Rep. 222(69), Ser. 4, Iss. 76, Space Sci. Lab., Univ. Calif. Berkeley, 35pp.

Haak, V., and Reitmayr, G.: 1974, 'The distribution of electrical resistivity in the Rhinegraben area as determined by telluric and magnetotelluric methods'. In J.H. Illies and K. Fuchs, (Eds.) *Approaches to Taphrogenesis*, Schweizerbart-Stuttgart, pp. 366-369.

Hempfling, R.: 1977, 'Beobachtung und Auswertung tagesperiodischer Variationen des erdelektrischen Feldes in der Umgebung von Göttingen', Dissertation des Doktorgrades, Fakult. der Georg-August, Universität zu Göttingen.

Hungarian Academy of Sciences: 1976, *Geoelectric and Geothermal Studies. East-Central Europe, Soviet Asia*, KAPG Geophysical Monograph, Akademiai Kiado Budapest, 750 pp., (1976).

Hutton, V.R.S.: 1976a, *Acta. Geodaet., Geophys. et Montanist. Acad. Sci. Hung.* 11(3-4), 347-376.

Hutton, V.R.S.: 1976b, *Rep. Prog. Phys.* 39, 487-572.

Kovtun, A.A.: 1976, *Acta. Geodaet., Geophys. et Montanist. Acad. Sci. Hung.* 11(3-4), 333-346.

Kunetz, G.: 1965, Personal communication.

Lefevre, C., Albertinoli, P., Bauer, A., Blum, A., Cagniard, L., and Fournier, H.G.: 1957, *Ann. Geophys.* **13**, 54-68.
Mbipom, E.W.: 1977, *Acta Geodaet., Geophys. et Montanist. Acad. Sci. Hung.* **12**(1-3), 11-17.
Mechler, P., Mseddi, R., and Plantet, J.L.: 1971, *C.R. Acad. Sci. Paris*, **273**, Serie D, 298-301.
Mosnier, J., and Babour, K.: 1978, Abstract, VIè Rěun. Ann. des Sc. de la Terre, Orsay.
Osipova, I.L., Berdichevsky, M.N., and Vanyan, L.L.: 1978, Abstract, Fourth Workshop on Electromagnetic Induction in the Earth and Moon, Murnau, Germany.
Pěčova, J., Praus, O., and Pěč, K.: 1977, *Acta. Geodaet., Geophys. et Montanist. Acad. Sci. Hung.* **12**(1-3), 407-415.
Porokhova, L.N.: 1975, *Fiz. Zemli* **5**, 47-53.
Reitmayr, G.: 1975, *J. Geophys.* **41**, 651-658.
Stegena, L.: 1976, *Acta. Geodaet., Geophys. et Montanist. Acad. Sci. Hung.* **11**(3-4), 377-397.
Tichonov, A.N.: 1950, *Doklady. Akad. Nauk SSSR.* **73**(2), 295-299.
Webster, T.F.: 1957, 'An experimental investigation of telluric and magnetotelluric phenomena', M.Sc. Thesis, Univ. Alberta.
Weidelt, P.: 1977, *Acta. Geodaet., Geophys. et Montanist. Acad. Sci. Hung.* **12**(1-3), 195-205.
Weise, H.: 1962, *Geofisica Pura E Applicata* **51**, 59-78.